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Creating Metallic Under-Dense Radiators by Electron Beam Heating Prior to Laser Impact

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A pulsed, relativistic electron beam can heat a metal foil to a plasma state, and initiate an expanding flow into vacuum. At a given time in its evolution, this flow fills a nearly spherical volume with nearly uniform density, assuming a rapid expansion prior to any condensation. A metal cloud produced in this way can serve as a target of intense laser illumination to create an under-dense radiator of x-rays. The phrase "under-dense radiator" means that the cloud, assumed ionized, has a plasma density that is less than the critical density for the wavelength of the laser light. The example described here is of a 2 μg copper foil 23 μm thick and 0.16 mm in diameter, heated by 8 mJ of electron beam energy in as short a time as possible, perhaps under 50 ns. The electron beam pulse must be at least 140 nC at 100 keV in order to transit the foil and deposit 8 mJ. A 50 ns pulse focused on the target would have a current of 2.8 A, and a current density of 14 kA/cm^2. The initial plasma temperature is 0.5 eV. After 300 ns, the flow has expanded to fill a nearly spherical volume of 1 mm diameter, with a nearly uniform copper density of 1.5×10^{20} cm^{-3}. The leading edge of the cloud is expanding at 1700 m/s, while flow at the original position of the foil surface expands at 150 m/s. This cloud is nearly stationary during the short time of a laser pulse at the National Ignition Facility (NIF).

Introduction

This article describes an idea for improving the efficiency of generating intense, multi-keV x-ray sources at laser-fusion facilities.

The critical electron density, in cm^{-3}, for laser wavelength λ, in μm, is $n_c = 1.12 \times 10^{21}/\lambda^2$. At 1.06 μm, $n_c = 1.05 \times 10^{21}$ cm^{-3}, and at 0.35 μm, $n_c = 1.0 \times 10^{22}$ cm^{-3}. Material below the critical density can be heated throughout its volume by laser illumination. Material above the critical density absorbs laser energy in a thin surface layer of plasma, which expands rapidly into the surroundings. Heat from this surface layer is also driven into the body of the over-dense material. This ablative heating of the over-dense interior advances at a much slower speed than the transit of laser light through an under-dense medium. See Reference 1 for a basic description of laser-fusion.

Under-dense material radiates a much higher proportion of the incident laser energy because little of this energy has gone into plasma acceleration. Under-dense targets may emit up to an order of magnitude more multi-keV photons than equivalently illuminated over-dense targets at the NIF laser, see Reference 2.

An ideal under-dense target would be a uniform, spherical, metallic cloud of 1 mm diameter. The 1 mm scale is typical of laser-fusion targets. Unfortunately, a static metal vapor at room temperature and a density equivalent to, say, 5 to 10 standard atmospheres would rapidly condense. However, such a cloud can exist as a momentary state of a rapid expansion. The idea here is to pulse-heat a solid target of appropriate size, with an electron beam, and expand it into the desired distribution of density just prior to laser illumination.

Flow model

The flow model used here was developed recently to analyze experiments on impulsively-heated metal by electron beam impact, see Reference 3. I intend to write a report on this work for a future presentation, Reference 4 notes the abstract.

The model begins with a uniformly-heated cylindrical volume of metal, which may be thin in comparison to its diameter. Flow is assumed to issue only from the faces, not the cylindrical periphery. All material is assumed to be an ideal perfect gas, and material within the original volume cools and rarefies adiabatically as matter flows at sonic velocity across the faces. The flow expands into vacuum with mirror-image symmetry, and with flow fronts whose shapes change as they progress away from their respective sonic cross sections.

The flow is analyzed by using the one-dimensional stream-tube-area relations, and an assumption about the nature of flow cross sections as a function of distance from the plate. See texts on supersonic flow for a description of the stream-tube-area relations, References 5 and 6 are examples. The model of cross section at distance is that each front can be constructed from a prior one by advancing material using Huygens' principle and the local supersonic speed. The flow front progresses from the area of the sonic disc to a distant hemispherical area, on each side of the plate. The area at axial distance z on each side of the plate is

$$A(z) = 2\pi(z^2 + \frac{\pi}{2}r_0 z) + \pi r_0^2 \tag{1}$$

where r_0 is the radius of the cylindrical source volume. Matter at the central cross section of the plate is static, at the surface areas it flows at Mach one, and Mach number increases with z as the flow accelerates to infinity. At distant time, the original volume is a cold void, and the flow is an expanding shell.

A copper flow

Consider the following example. A copper disc 23 μm thick and 0.16 mm in diameter is heated by an impulse of 8 mJ of energy. The history of the average density of the source volume is shown in Figure 1. The source density diminishes to less than a standard atmosphere by 1 μs. The source temperature drops from 0.5 eV to room temperature (300° K) by 0.2 μs, see Figure 2.

Figure 3 shows a profile of copper density as a function of axial distance z at 300 ns (0.3 μs). The front has reached 0.5 mm, and the density is between 1.0×10^{20} cm^{-3} and 2.0×10^{20} cm^{-3}. The density between the sonic sections is somewhat higher, 3.0×10^{20} cm^{-3}. The thickness of the solid target is shown for comparison to the extent of the flow.

Figure 4 shows the velocity at a given distance z at 300 ns, the front is moving at 1.7 km/s. During a 2 ns laser pulse the flow would expand only an additional 3.4 μm.

An idea of the density distribution at 300 ns is given by Figure 5. Here, contours of constant density are shown on a radial-axial grid measured in mm. The density is reasonably uniform throughout most of the hemispherical volume, with most of the variation near the initial volume.

If heat is added to the solid target too slowly, some of the material may expand outside of the focal spot of the electron beam during its course. Figure 6 shows a profile of copper density at 100 ns after impulsive heating, this is just an earlier view of the flow already described. Here, the front has reached 0.15 mm. If electron beam heating were to occur over 100 ns, then it might be necessary to have a focal spot as wide as 0.5 mm, and a larger charge, to ensure that all the copper achieved the desire specific energy of 4 kJ/g.

Figure 7 shows the copper density profile at 50 ns, the front is at 0.06 mm. Figure 8 shows the density contours at 50 ns for the 8 mJ, 2 μg copper flow. The radial cross section of the initial solid target is shown for comparison to the extent of the flow. The cloud is oblong, being 0.3 mm by 0.14 mm in radial cross section.

The efficiency of converting electron beam energy to heat should improve as the heating pulse is shortened. Thus, it is desirable to have a high-power electron beam. The likelihood of condensation decreases as the heat energy increases. This is accomplished by increasing the charge of the electron beam pulse. The kinetic energy of the electron beam should be high enough to completely penetrate the solid target, here above 100 keV. An ideal electron beam would have the minimum power, charge, and voltage to create the desired metal cloud.

Electron beam parameters

An electron beam pulse of at least 140 nC at 100 keV, an energy of 14 mJ, is needed in order to transit the 23 μm thick copper foil and deposit 8 mJ. The energy is transferred by collisions, and this quantity is calculated from Bethe's stopping power theory, see References 7 and 8. A 50 ns pulse focused on the target would have a current of 2.8 A, and a current density of 14 kA/cm^2. The electron beam source would have to supply 280 kW at 100 kV with a 50 ns pulse, or more power with shorter pulses.

The electron beam desired for this application must come from a high-perveance ($> 1 \times 10^{-6}$ $A/volt^{3/2}$), high-current (> 10 A/cm^2)

device. The entire assembly might consist of a cathode, an accelerating section, and an electrostatic or magnetic focusing section. The high-current cathode might be a thermionic source, a laser-driven photocathode, or a surface plasma source. A high-current laser-driven photocathode would have the advantage of being able to provide short pulses by tailoring the laser pulse. These electron beam sources are described in Reference 9.

The next step

This analysis reduces the problem of creating metallic under-dense radiators to the problem of providing a practical electron beam device with parameters as described. The next step would be to enumerate the details of such a device, and then determine the cost and effort required to implement this scheme.

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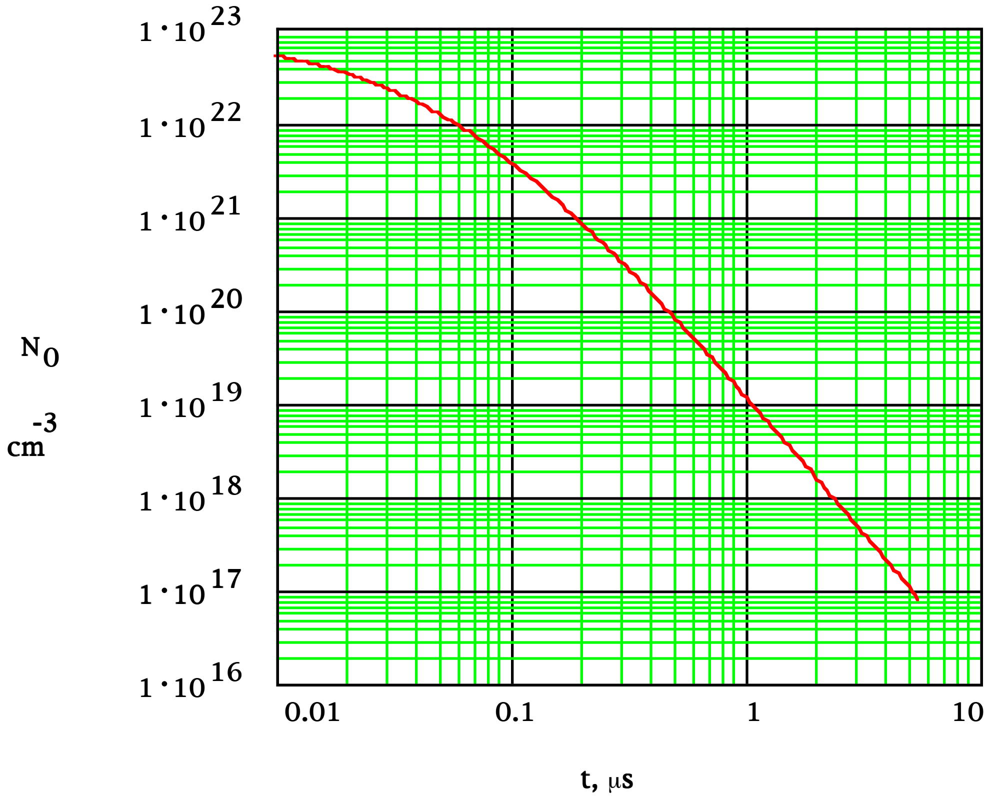

Figure 1, Source number density history at 8 mJ
Atom density in cm^{-3} at time in μs within original plate volume after an 8 mJ heating impulse. Copper at 23 μm, 0.16 mm diameter.

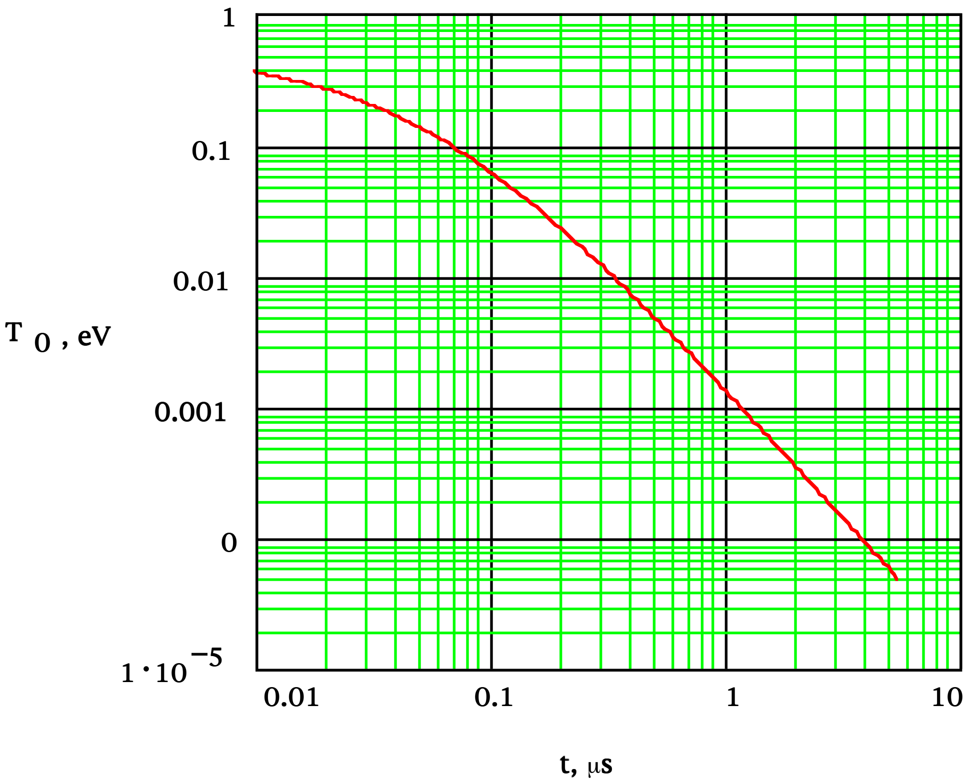

Figure 2, Source temperature history at 8 mJ
Temperature in eV at time in μs within original plate volume after an 8 mJ heating impulse. Copper at 23 μm, 0.16 mm diameter.

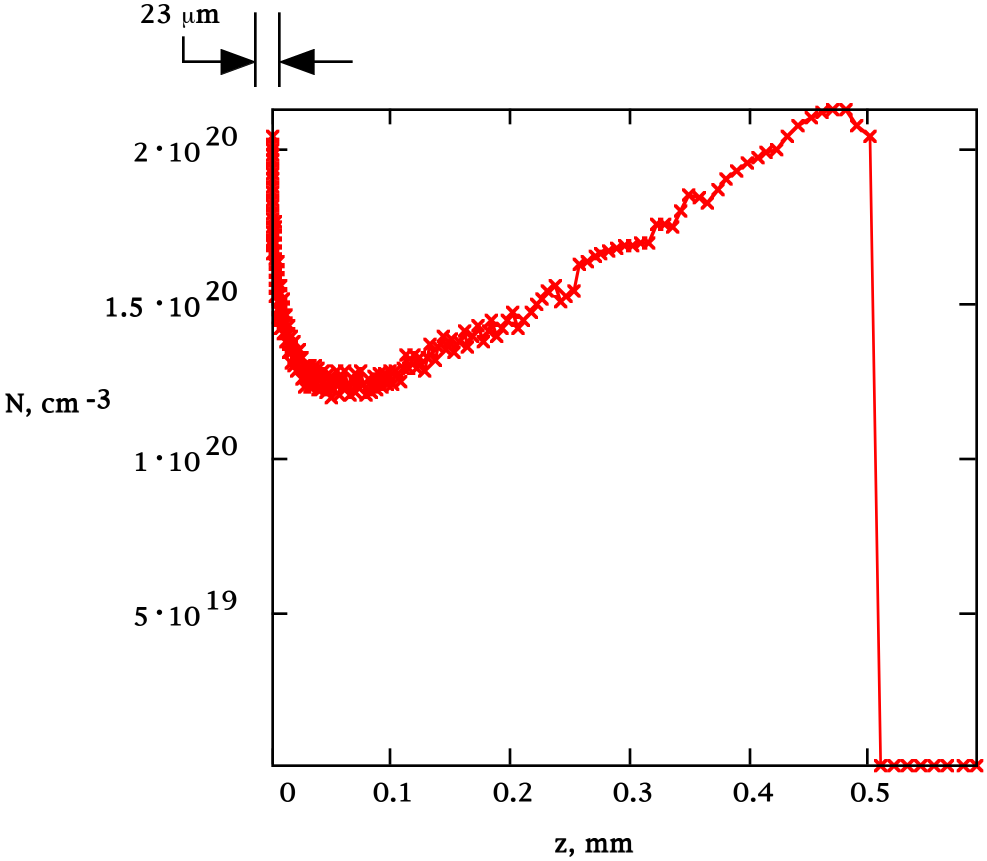

Figure 3, Cloud number density profile at 300 ns
Atom density in cm^{-3} at distance in mm from plate surface at 300 ns after an 8 mJ heating impulse. Copper at 23 μm, 0.16 mm diameter.

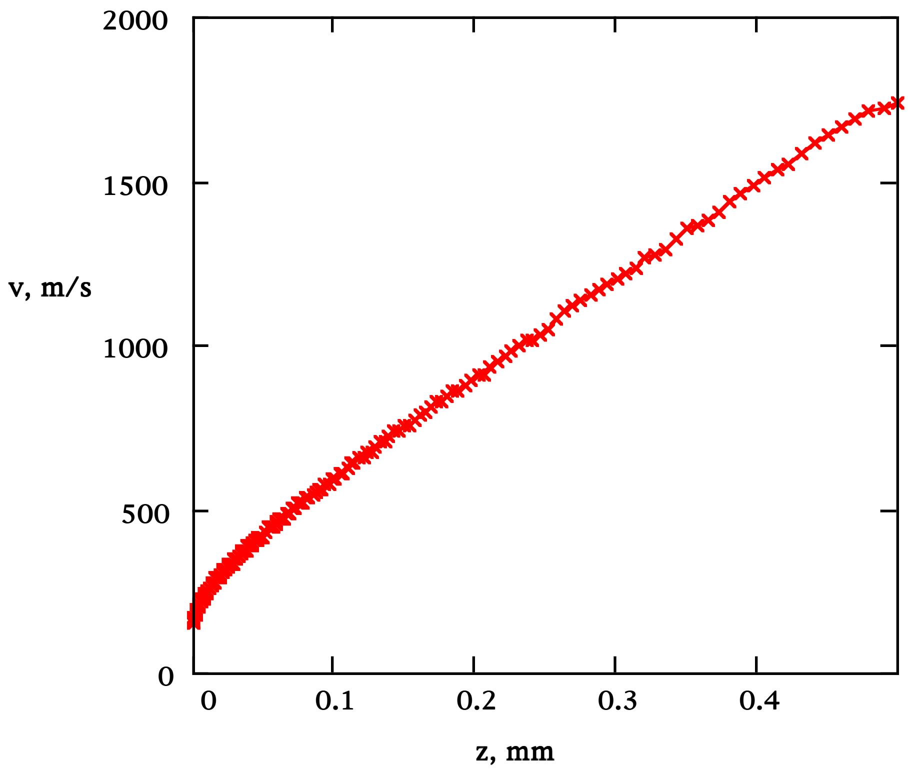

Figure 4, Cloud velocity profile at 300 ns
Velocity in m/s at distance in mm from plate surface at 300 ns after an 8 mJ heating impulse. Copper at 23 μm, 0.16 mm diameter.

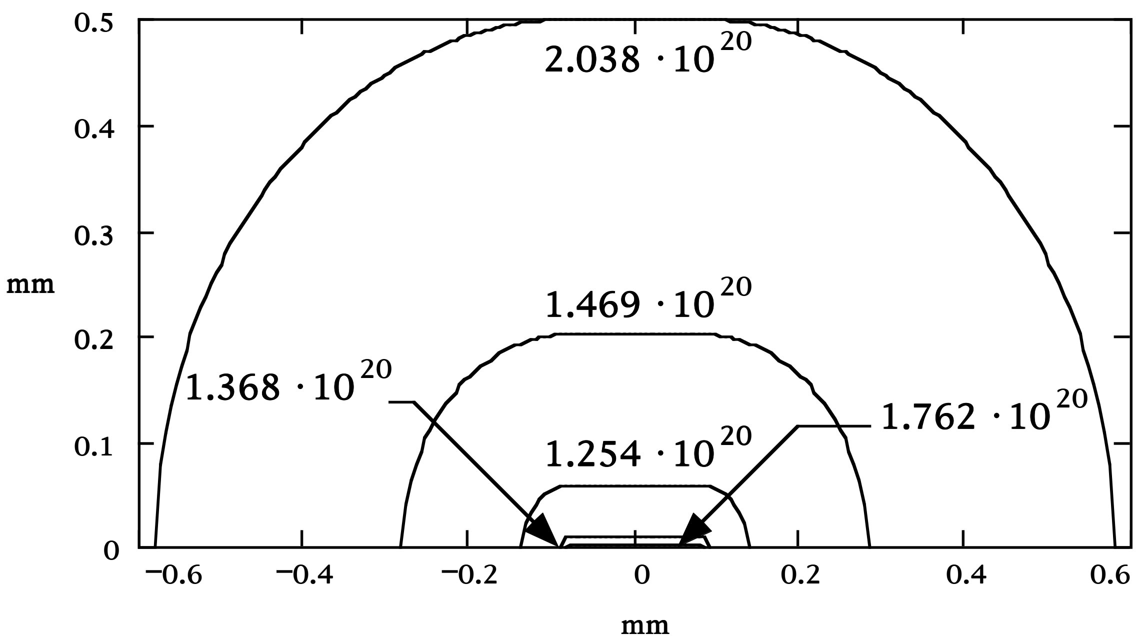

Figure 5, Cloud density contours at 300 ns

Density contours in cm^{-3} at distance in mm from plate surface at 300 ns after an 8 mJ heating impulse. Copper at 23 μm (vertical), 0.16 mm diameter (horizontal).

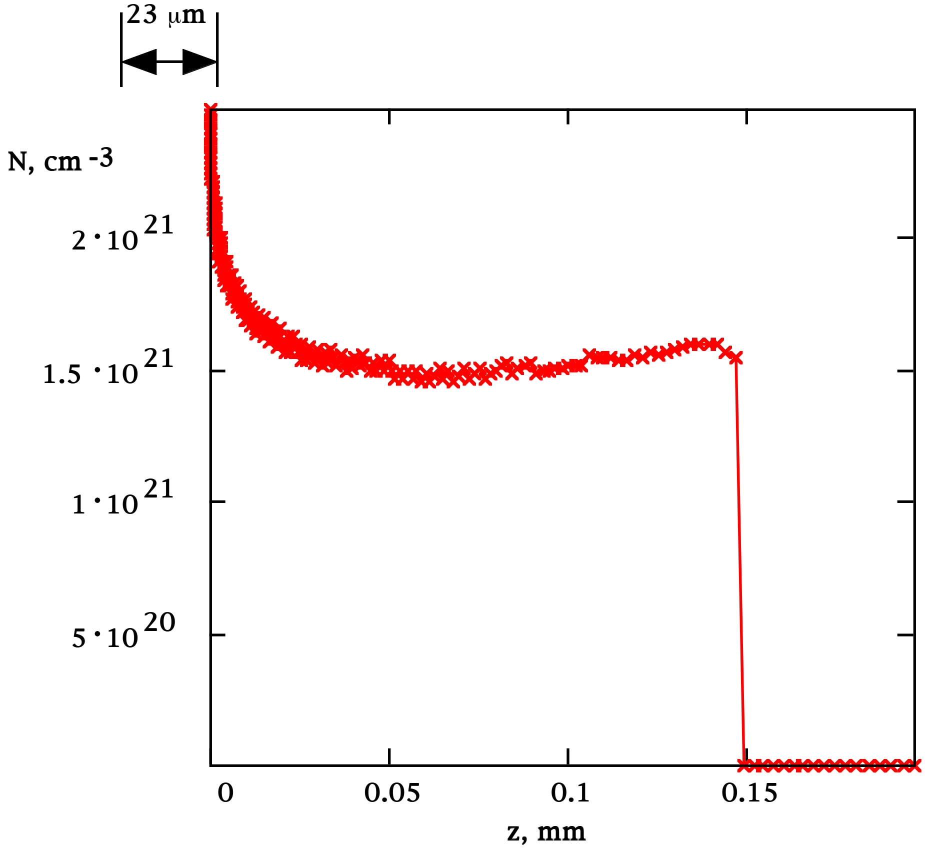

Figure 6, Cloud number density profile at 100 ns
Atom density in cm^{-3} at distance in mm from plate surface at 100 ns after an 8 mJ heating impulse. Copper at 23 μm, 0.16 mm diameter.

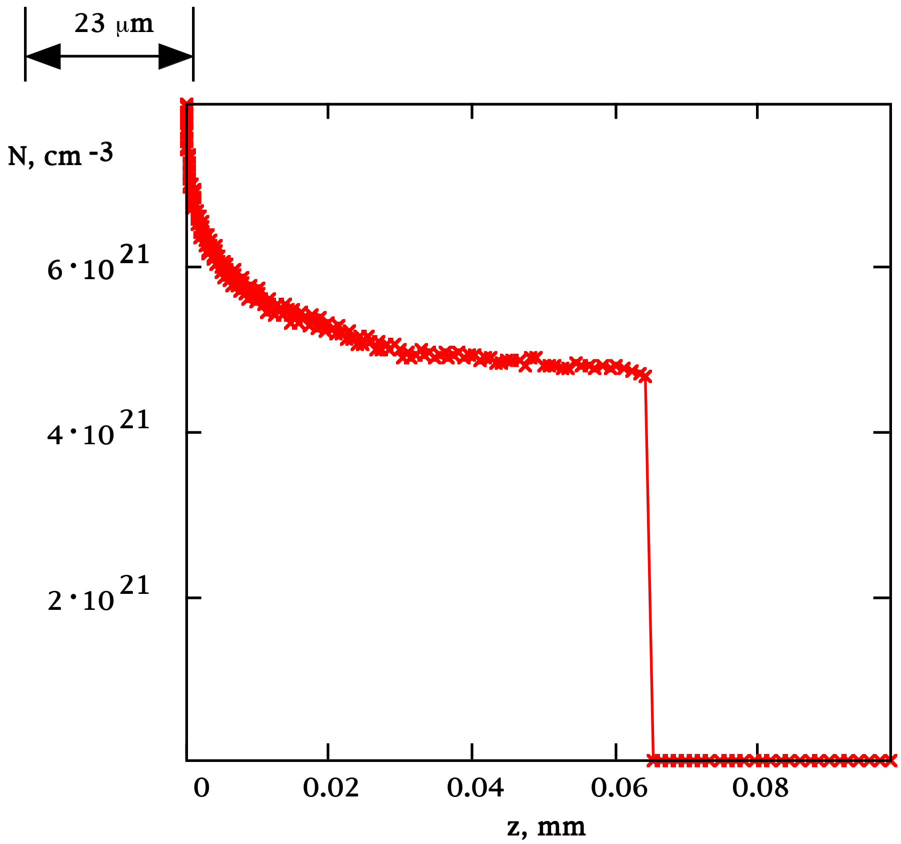

Figure 7, Cloud number density profile at 50 ns
Atom density in cm^{-3} at distance in mm from plate surface at 50 ns after an 8 mJ heating impulse. Copper a 23 μm, 0.16 mm diameter.

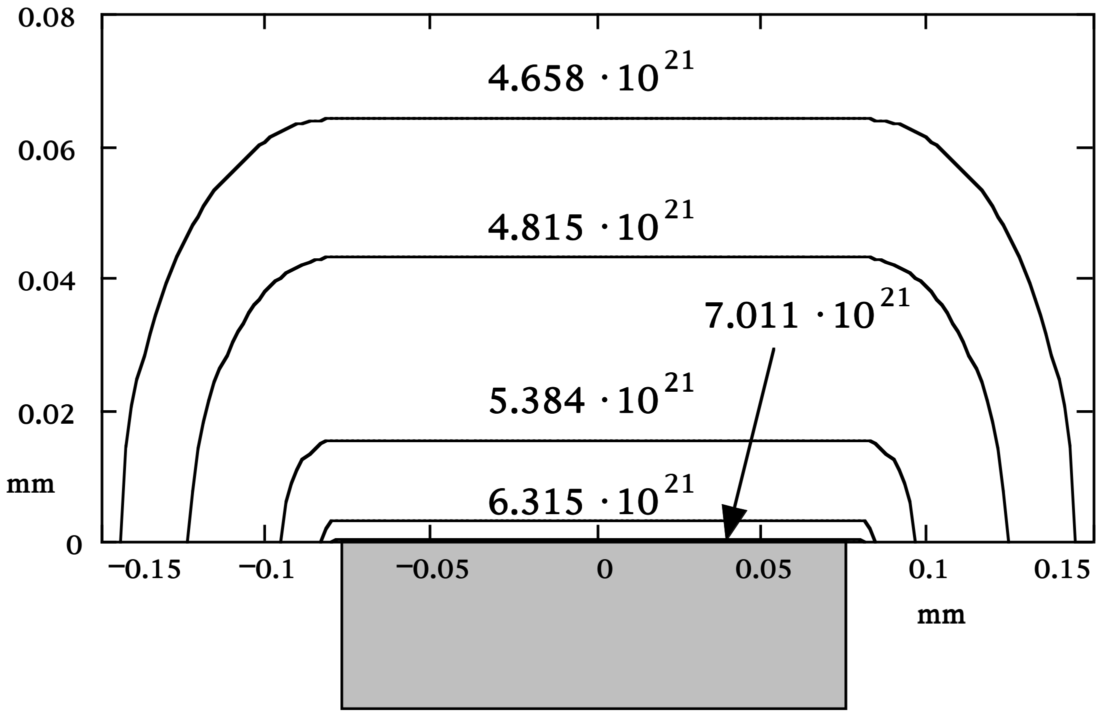

Figure 8, Cloud density contours at 50 ns

Density contours in cm^{-3} at distance in mm from plate surface at 50 ns after an 8 mJ heating impulse. Copper at 23 μm (vertical), 0.16 mm diameter (horizontal). Original cross section shown with shading.